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PRELIMINARY REACTOR IMPLICATIONS OF COMPACT TORI: HOW SMALL IS COMPACT?

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I. INTRODUCTION

The generic name "compact torus" (CT) is applied to the general class of toroidal plasma configurations in which no magnetic coils or material walls extend through the torus. Figure 1 schematically summarizes the "family tree" of CT configurations that have been subjected either to theoretical or experimental examination. Two branches to the CT family of closed-field plasmoids are evident. Ongoing reactor studies at LASL have focused primarily onto the left-hand branch depicted in Fig. 1, with an emphasis being placed upon field-reversed theta pinch (FRΘP) as a means to form, heat and confine a CT plasmoid in a reactor context. Both the spheromac and the FRΘP configurations are assumed to require an electrically conducting wall to provide equilibrium and stability. The purpose of this paper is to present parametrically and by means of a simple analytic model the reactor implications of a FRΘP; an electrically conducting shell is presumed necessary for equilibrium and stability. The question of mimimum power and size for this specific CT configuration is addressed.

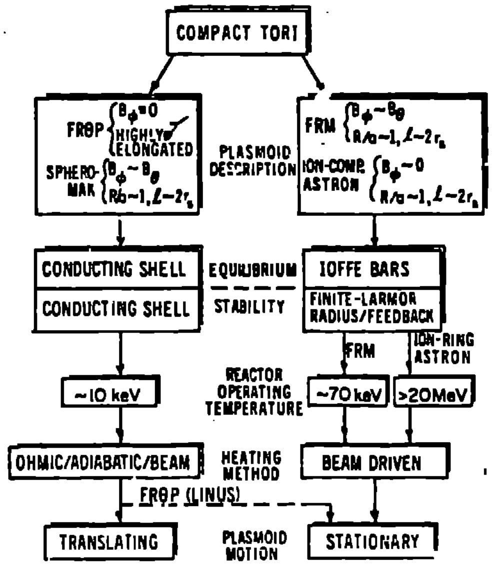

Figure 1
Schematic summary of compact torus plasma configurations.

II. MODEL

A. GENERAL CONSIDERATIONS

Figure 2 depicts the CT model and pertinent notation that form the basis for this analysis. Experimental evidence indicates[1] decreased confinement times as r_c/r_s increases beyond ~ 2 and the plasma becomes overcompressed. The experimental parameters $r_c/r_s \sim 2$ and $\ell/r_s \sim 7$, along with analytic equilibrium constraints, are used to guide this study. As is observed in experiments, the FRΘP plasmoid is assumed to contain little or no toroidal field. The question of plasmoid formation and heating is not addressed here, although these processes would occur in an exreactor system by means of slow implosion, adiabatic heating, the application of energetic particle beams, and/or ohmic dissipation.

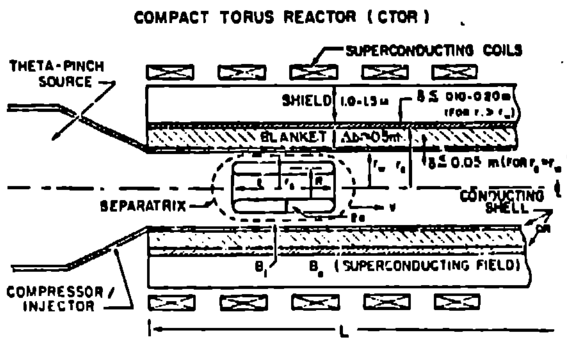

Figure 2
Schematic layout of Compact Torus Reactor (CTOR) based on FRΘP. Conducting shell is shown located either at first wall or outside of blanket.

Given the formation, heating, and translation of the FRΘP plasmoid, how best can useful fusion energy be obtained from a shell-stabilized configuration, and in which way does this constraint affect the projected reactor size and power level if realistic engineering constraints are applied? In short, how small is compact?

B. ROLE AND LOCATION OF CONDUCTING SHELL

A central thesis of this study is the presumption that a passive, electrically conducting shell provides both equilibrium and stability and that r_c/r_s must be ≤ 2 for this to occur. The heated and ignited plasmoid of length ℓ enters the linear burn chamber of length L and radius r_w at a velocity $v = L/\tau_B$ that is compatible with the electrical skin time, τ_s, of the conducting shell positioned at radius $r_c > r_w$. Translation of the plasmoid inside this flux-conserving shell increases the stationary magnetic field (provided by external superconducting magnets, Fig. 2), as magnetic flux is constricted to a smaller volume between the separatrix and the shell. That part of the plasma pressure supported by the conducting shell results in ohmic dissipation within shell which must be extracted from the translational energy of the plasmoid. This energy loss may be significant and generally points to the use of a room-temperature shell located outside a blanket of thickness Δb.

As the plasmoid is translated to the burn chamber, the flux within the shell, provided initially by the external superconducting coils, is conserved. A characteristic time, τ_s, for flux penetration into the shell of resistivity η can be derived on the basis of this flux conservation

$$\tau_s = \frac{\mu_o}{2\eta}\frac{\delta}{r_c}\left(r_w^2 - r_s^2\right) \quad . \tag{1}$$

This expression is based upon an allowable flux loss as determined by the limit when the plasmoid would contact the first wall. Placement of the shell at the first wall (i.e., $r_c \simeq r_w$) will require that the shell thickness, δ, be less than ~ 0.05 m for neutronic reasons; additionally, η will be increased because of the higher operating temperature at a first-wall location. Generally, τ_s is computed to be 3-4 times longer if the shell is positioned outside the blanket, inspite of the higher value of $r_c \simeq r_w + \Delta b$. Even when located outside the blanket, the shell thickness should present a cross-sectional area that is appreciably smaller than the crucial area from which flux is being displaced (i.e., $\pi(r_w^2 - r_s^2)$). Furthermore, the ohmic power dissipated in the shell, P_{OHM}, when expressed relative to the alpha-particle power, P_α, is given by

$$P_\alpha/P_{OHM} = 8.6(10)^{16}\,\frac{\delta}{\eta}\,\frac{r_c^3}{r_s^2}\,\frac{\langle\sigma v\rangle}{T^2}\,B_i^2 \quad , \tag{2}$$

where B_i is the compressed magnetic field within the shell. For typical reactor parameters ($r_w = 1.0$ m, $\Delta b = 0.5$ m, $B_i = 5$ T), this ratio decreases from ~ 60 for an ex-blanket shell ($\delta = 0.1$ m) to ~ 4 ($\delta = 0.05$ m) for a first-wall shell, again giving impetus to shell placement outside the blanket. Lastly, the ohmic dissipation occuring within the shell must be provided either by the kinetic or the fusion (i.e., directly converted alpha-particle energy) powers associated with the translating, burning plasmoid. For a first-wall shell, the required translational power can be considerable, and the plasma expansion required to channel directly the alpha-particle energy to supply this ohmic loss would be prohibitively large. On the basis of these arguments, the stabilizing conducting shell should be located at a radius $r_c = r_w + \Delta b$, where Δb is expected to be ~ 0.5 m. In order to provide the necessary stabilization of a plasmoid of length $\ell \simeq 7\ r_s$, the translational velocity must be $v = \ell/\tau_s$, again with $r_c/r_s \simeq 2$. As will be seen, these simple constraints play .. important role in establishing the minimum size and power of the CT reactor.

C. CONSTRAINTS IMPOSED BY NEUTRON WALL LOADING AND TOTAL POWER

The fusion neutron wall loading, $I_w(W/m^2)$, and a Lawson-like criterion, $n\tau_B$ (s/m^3), at this level of analysis represent important indicators of system performance. The analytic CT equilibrium relationships predict that 87% of the plasmoid volume within the separatrix radius, r_s, would be filled with $\beta \simeq 1$ plasma. The fraction of the burn chamber that is filled with plasma (i.e., the duty factor), is easily shown to equal τ_s/τ_I, where $1/\tau_I$ is the plasmoid injection rate. Recalling that the burn time, $\tau_B = \tau_s(L/\ell)$, the following expression for I_w results

$$\frac{9.02\ I_w\ \tau_I}{(n\tau_B)^2\ \langle\sigma v\rangle\ E_N} = \frac{r_s^2}{r_w}\frac{\tau_s}{\tau_B^2} = \frac{r_s^4}{2r_s - \Delta b}\frac{(\ell/r_s)^2}{L^2\tau_s} \quad , \tag{3}$$

where mks units are used, E_N is the fusion neutron energy, $r_w = r_c - \Delta b$, $r_c/r_s \simeq 2$, $\ell/r_s \simeq 7$, and τ_s (Eq. (1)) can similarly be expressed in terms of r_s. With the exception of τ_I, the left-hand-side of Eq. (3) represents a constant that is chosen on the basis of confinement physics, $n\tau_B$, and desired system performance, I_w. The total system thermal power, P_{TH}(Wt) equals $2\pi r_w\ L\ I_w\ M$, where the multiplication M is typically ~ 1.42 (20 MeV/fusion). For a given wall loading and $n\tau_B$ value, therefore, P_{TH} can be evaluated as a function of system dimensions (i.e., r_s and L).

An additional and important constraint is imposed by the allowable thermal cycle, ΔT(K), experienced by the first wall. The thermal heat flux at the structural first wall is expected to originate primarily from Bremsstrahlung radiation, in that particle losses should be directed out of the burn chamber along open field lines in the region from radius r_s to r_w. If k(W/mK), ρ(kg/m^3) and c_p(J/kg K) are, respectively, the thermal conductivity, density, and heat capacity of the first-wall material, the temperature rise for a "thermally thick" first wall that is irradiated solely by Bremsstrahlung leads to the additional constraint

$$\frac{\Delta T\sqrt{c_p k\rho}}{2.63(10)^{-37}\ (n\tau_B)^2 T^{1/2}} = \frac{r_s^2}{r_w}\left[\frac{\ell}{L}\right]^2\frac{1}{\tau_s^{3/2}} = \frac{r_s^4}{2r_s - \Delta b}\frac{(\ell/r_s)^2}{L^2\tau_s^{3/2}} \quad , \tag{4}$$

where T(keV) is the average plasmoid temperature, and the thermal irradiation time experience by any given section of first wall is taken as τ_s.

III. RESULTS

Typical results are illustrated on Fig. 3, which shows the dependence of P_{TH}, L, and τ_s on the separatrix radius for the fixed parameters indicated. A minimum total power is shown for this case where the duty factor, $f_\ell = \tau_s/\tau_I$, has been fixed at 0.1 and $n\tau_B = 5(10)^{21}$ s/m^2 (i.e., a fuel burnup fraction $f_B = 0.22$). The reactor power initially decreases with increased r_s because of the increased τ_s and correspondingly decrease in required translational

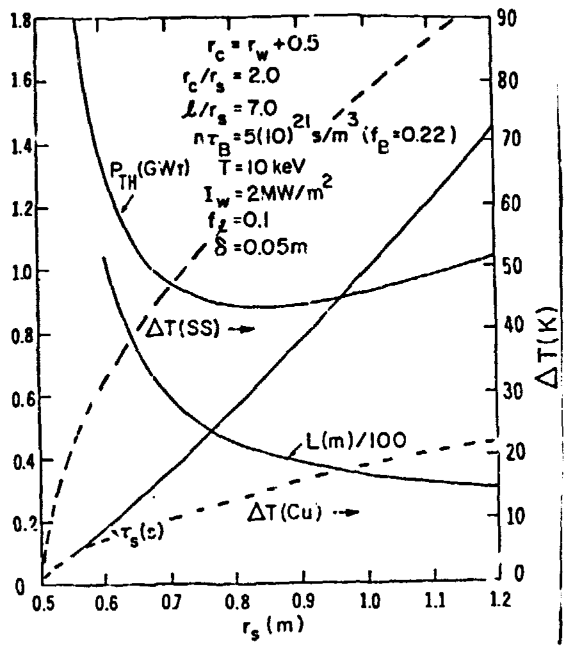

Figure 3

Dependence of total power, P_{TH}, length of burn chamber, L, and shell skin time, τ_s, on plasmoid separatrix radius, r_s, for the fixed parameters indicated.

velocity; an increased reactor length results. As r_s increases beyond the power minimum at 0.83 m, the power increases because of the increased plasma cross-sectional area. Only the magnitude but not the position of the minimum power indicated on Fig. 3 depends on the choice of fixed parameters, Eq. (3) providing the appropriate scaling relationship. Specifically, combining Eq. (3) with $P_{TH} = 2\pi r_w L I_w M$ gives the following explicit form for the power curve depicted on Fig. 3.

$$P_{TH}(Wt) = 8.78\, M I_w^{1/2} \langle\sigma v\rangle^{1/2} (\eta/\delta)\, \Delta b^{3/2}$$

$$f_\ell^{1/2} \frac{(1-x)^{1/2}}{x^{3/2}\left[(1-x)^2 - 1/4\right]} \quad , \qquad (5)$$

where $x = \Delta b/r_c = \Delta b/2r_s$. Equation (5) shows the expected minimum at $x = 0.3$ (i.e., $r_s = 0.83$ for $\Delta b = 0.5$ m). For T = 10 keV, M = 1.42 and $\eta = 2(10)^{-8}$ ohm m (Cu at 300 K), the minimum power equals

$$\check{P}_{TH}(Wt) = 5.54(10)^{-17}\, I_w^{1/2}\, \Delta b^{3/2}$$

$$f_\ell^{1/2}\, (n\tau_B)/\delta \quad , \qquad (6)$$

which illustrates explicity the CTOR mimimum-power scaling. Because of the direct coupling of plasma performance with the ex-blanket shell, Δb plays a prominent role in establishing the minimum power. Furthermore, contrary to intuition, the minimized total power varies weakly as the square root of the first-wall neutron wall loading. For the minimum power shown on Fig. 3, the following system characteristics are predicted: P_{TH} = 880 MWt, L = 42 m, r_s = 0.83 m, ℓ = 5.8 m, r_w = 1.2 m, r_c = 1.7 m, τ_s = 0.6 s, τ_B = 4.5 s, τ_I = 6.2 s (f_ℓ fixed at 0.1), v = 9.4 m/s (34 km/h), n = $1.1(10)^{21}$ m^{-3}, B_i = 3 T, $P_{TH}/\pi r_c^2 L$ = 2.4 MW/m^3.

The temperature-rise constraint given by Eq. (4) is expressed below in explicit form

$$\Delta T = 8.33(10)^{-28} \left[\frac{(1-x^2)-1/4}{x}\right]^{1/2} \left[\frac{\delta \Delta b}{c_p \rho k n}\right]^{1/2} \frac{I_w}{(\langle\sigma v\rangle/T^{1/2}) f_\ell} \quad , \qquad (7)$$

which predicts ΔT = 14.2 K at the minimum-power point for a first wall with thermophysical properties of copper. Equation (7) has been plotted on Fig. 3 for first walls with both stainless-steel and copper thermophysical properties. Application of the thermal cycle constraint, $\Delta T \leq 30$ K, requires that τ_B to be adjusted to ~ 3.2 s and f_ℓ correspondingly be reduced to ~ .05, resulting in an optimum (i.e., minimized) reactor power of 600 MWt with L = 30 m, again for a first wall with thermophysical properties similar to copper. Stainless steel represents an extreme relative to the assumed copper-like first-wall properties, representing an increase in ΔT by a factor of $\sqrt{(kc_p\rho)_{Cu}/(kc_p\rho)_{SS}} = 4.4$. It is emphasized that the methods used to estimate the thermal-cycle constraint are highly approximate, and considerably more analysis of this important and often neglected problem is warranted.

IV. CONCLUSIONS

The application of simplified but realistic engineering constraints to the special class of wall-stabilized FRΘP configurations leads to reactor systems that may be as small as ~ 30 m in length and generating a total thermal power of the order of 500 MWt. Decreased size and power for a given $n\tau_B$ will be accompanied by decreased performance indicators, as reflected in this study by I_w and the allowable ΔT. It should be noted that this analysis is based upon fixing the duty factor, $f_\ell = \tau_s/\tau_I$. Other approaches which treat τ_I rather than f_ℓ as a parameter give somewhat different optima, but the basic conclusions and results embodied in Fig. 3 are not significantly altered. The results of this simple scoping calculation will be used to guide a more detailed modeling of important issues related to plasmoid injection, plasma transport/equilibrium/stability, burn dynamics, transient response of the the first wall and conducting shell, and overall system energy balance.

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